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Synthetic Digital Model for Stability Performance Assessment in the Future Dutch Power System

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***Abstract*—The exponential increase in the integration of Variable Renewable Energy Sources and responsive storage, compensation, and prosumers in electrical power systems raises many uncertainties that affect the operation, control, and planning across different time horizons. Dynamic stability refers to a system's ability to withstand and recover from disturbances while ensuring that systemic symptoms (e.g., voltages, currents, frequency, angular displacements) remain within acceptable limits under both normal and abnormal conditions. Unacceptable excursions in systemic symptoms can cause disruptions or blackouts. A suitably developed and calibrated digital model for dynamic simulations is a key tool for this purpose. This manuscript overviews the development of a digital synthetic model for in-depth analysis and identification of the occurrence and propagation of potential instability issues. The synthetic model is inspired by accessible data on the hypothetical future situation (e.g., year 2030) of the Dutch Power System. The model has been built on the basis of generic component models and parameters from the literature, and several disturbances are evaluated by time-domain simulations. Renewable power electronic-interfaced generators and remaining synchronous generators have implemented emerging methods to provide primary control for active and reactive power support in line with the state-of-the-art recommended practice. This model is proposed as the basis for studying different stability phenomena and challenges for controller design in future operating conditions of the Dutch system in light of the large-scale addition of renewable generation.**

***Index Terms*—Energy transition, digital model, dynamic stability, power system control, renewable generation, RMS simulation.**

I. INTRODUCTION

The Dutch power system aims to be fully renewable by 2045 [1], with a strategy focused on large-scale wind and solar photovoltaic (PV) integration. This transition requires infrastructure modernization through advanced storage and innovative technologies to improve efficiency, reliability, and sustainability.

Recent research emphasizes stability management in power systems [2], particularly due to fast voltage and frequency excursions caused by the rise of power electronic converters. While individual converters manage local control, system-level coordination remains essential for large-scale operation [3]. Dynamic models help mitigate issues such as voltage fluctuations in solar PV systems [4] and abrupt frequency or voltage changes in wind integration [5]. In addition to power electronics, intelligent control techniques are being explored for configurations involving photovoltaic, wind, hybrid variable renewables (VRES) and energy storage systems (ESS) [6].

Implementing coordinated control strategies with generators improves system stability. To analyze and compare dynamic behavior, benchmark test systems or synthetic models are commonly used [7], [8]. On a large scale, synthetic models support applications such as monitoring, analysis, visualization, and prediction. However, real-time data acquisition and processing methods remain underdeveloped [9].

Despite their value, synthetic models often lag in adopting emerging technologies like HVDC/MVDC systems and electric vehicles [10]. To accelerate this adoption process, cross-disciplinary standards, such as co-simulation frameworks, are under development [11]. Currently, no synthetic model of the Dutch power system is available for research purposes on steady-state and dynamic performances.

To accommodate the unexpected level of VRES integration, which are highly inverter-based, adequate research is necessary to avoid disturbances in the system that may trigger a series of events that could lead cascading failures, ultimately resulting in blackouts. A synthetic digital model is designed to investigate the effects of various events on the dynamic stability performance of a hypothetical futuristic situation of the Dutch power system. By examining the influence of the state-of-the-art considered control strategies on different controllable devices (e.g., renewable generators), suggestions are made to mitigate instability issues and strengthen power system resilience. Addressing major concerns with the rising

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penetration of VRES, such as inertia and frequency [12] [13], is taken into account.

The rest of the paper is organized as follows. Section II reviews the model configuration and its development. Relevant simulation results are discussed in Section III. Section IV concludes the principal findings of the present research, and some recommendations for further research are presented in Section V.

II. DEVELOPMENT OF THE SYNTHETIC DIGITAL MODEL OF THE DUTCH NETWORK

A. *Overview of the Model*

The dynamic model was initially built upon steady-state digital models previously developed in [14], [15]. It was further completed using publicly available data from public technical reports [16] and the website HoogspanningsNet [17]. The model is structured into different geographical zones and voltage levels. The different regions are depicted in the Fig. 1 within the single line diagram of the PowerFactory model.

The baseline model includes system components such as busbars (110/150/220/380 kV), generators (synchronous and static), transmission lines, loads (general load type), and interconnections to neighboring systems and distribution networks (modeled as general loads with power consumption equal to the corresponding power flow). Gas and WKK generators (cogeneration—combined heat and power, or *Warmtekrachtkoppeling*) are consolidated into a single gas generator. Renewable sources, such as wind and photovoltaic plants, are included and modeled as static generators.

B. *Model Development Process*

The model development involves multiple steps like control model selection, DSL composition and model calibration. The procedure is presented in Fig. 2.

After studying the specific requirements expected of each power-generating module, such as voltage regulation, frequency response, and power system stabilization, dynamic models are added to the generating sources. Composite models tailored to the specific characteristics of each synchronous generator are created to simulate the power system's dynamic behavior over time. After initialization, events and disturbances are introduced at various model components to analyze the system response. The model then undergoes final refinement before further testing.

Two scenarios are assumed for varying dispatches and load demands:

- **Base Case Scenario:** This scenario represents the operation of the power system under normal conditions, characterized by steady load demand, stable operation, conventional generation, and the absence of unusual events. The generators designed and modeled for simulation are listed in [18]. Generation is not evenly distributed across the various HV and EHV regions. Demand is modeled based on the distribution of peak demand, using recorded dispatches from 2017, 2018, and 2019.

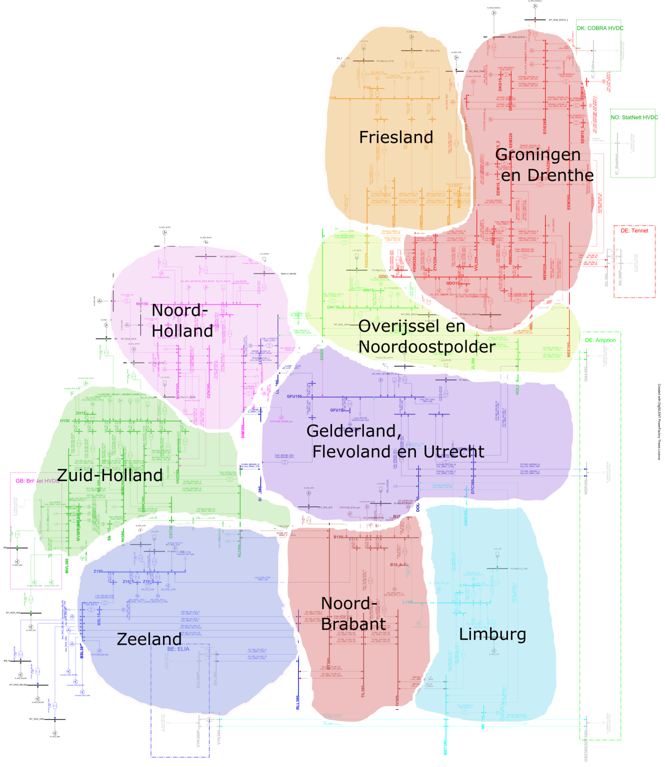


Fig. 1. Dutch power system division into zones

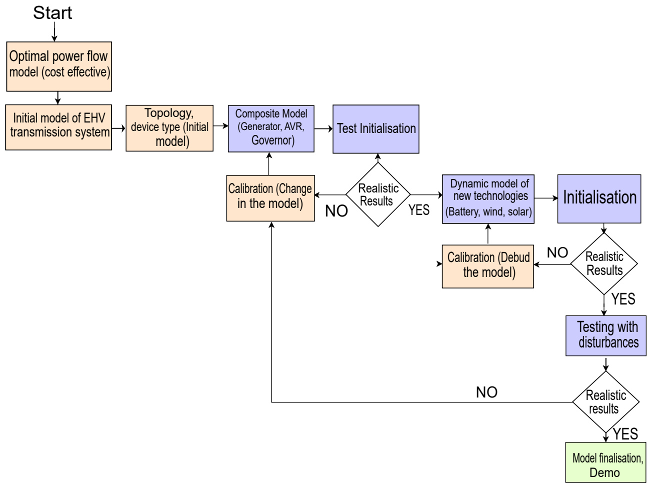


Fig. 2. Development process of the dynamic simulation model.

- **High Renewable Energy Integration 2030:** In this scenario, the total amount of conventional generation gradually decreases as the years progress. After adding VRES, the impact of this integration is evaluated. The share of renewable and conventional generation was set according to public target grid reports as [16].

After establishing different study cases in each scenario, the impact of each variation is studied. Finally, dynamic simulations are performed to evaluate the model's stability and security, and to identify areas of the system that are vulnerable. To perform all the steps mentioned, Python scripts are developed to avoid manual errors when inputting essential values and tuning variable parameters. The input parameters for dispatches and installed capacities are adjusted in Excel. Functions are developed to perform RMS simulations for each study case, which are changed in Python and initialized in PowerFactory. After initialization, the script sets installed capacities for the operational scenario and adjusts reactive power controls in PowerFactory.

C. Dynamic Model Selection

1) Synchronous Generators: Implementing dynamic models for synchronous generators ensures stable operation under varying operating conditions [19]. A synchronous generator composite frame, which follows the general block diagram in Fig. 3, is used from the DIgSILENT library to implement the exciter, governor, and power system stabilizer.

- **Exciter:** It provides DC power to the synchronous machine field winding, constituting the power stage of the excitation system. *IEEE-type AC1A* exciter model is integrated into the overall model, utilizing alternators as sources for the main generator's excitation power.
- **Governor:** Its function is normal speed/load control, overspeed control, and overspeed trip. *IEEEG1*, which is currently used, is the IEEE-recommended governor model for steam turbines.
- **Power System Stabilizer:** It uses auxiliary stabilizing signals to control the excitation system to improve power system dynamic performance [19]. *PSS1A* type stabilizer is currently used in dynamic simulations.

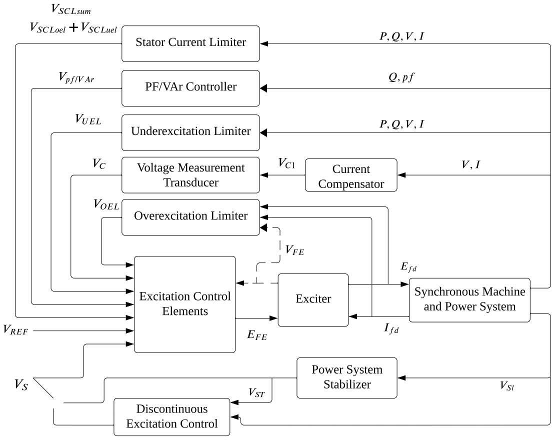


Fig. 3. General block diagram for synchronous machine excitation control system [20]

2) Photovoltaic Power Generation Systems: WECC Generic PV Plant Model was selected as the dynamic model in the PV generation systems [21]. It is a positive-sequence model representing the principal dynamic behavior of Large-scale PV systems. Developed by the Western Electricity Coordinating Council (WECC) in the Renewable Energy Modeling Task Force, this model allows assessment of the impact of PV plants on the dynamic stability of the power system.

The Dynamic Model includes the following modules:

1) **REGC_A**: To provide current injections, the generator converter module balances the current commands with the boundary conditions.
2) **REEC_B**: Active and reactive power references are converted into commands for current flow by the electrical control module.
3) **REPC_A**: The plant controller module will generate active and reactive power references using values from the system solution.

The composite frame of the general WECC Large-scale PV plant is presented in Fig. 4

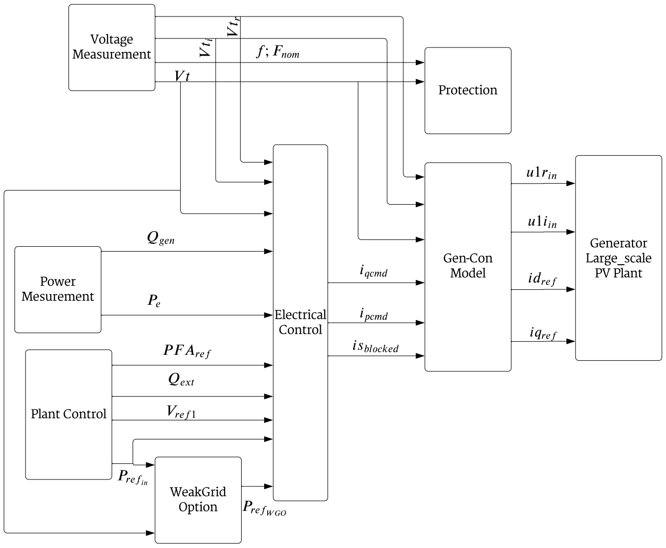


Fig. 4. Composite frame model of WECC large-scale PV systems [22]

D. Wind Power Generation Systems

Three different Control Systems for the wind generation systems are tested.

- **IEC Type 4B**: Ensures optimal power generation
- **Virtual Synchronous Machine**: Imitates a synchronous generator
- **Droop Control System**: Imitates a governor in a synchronous generator dynamic model.

Type 4 WTG generators are recommended because of their high efficiency, high power density, and dependability. Emerging technologies that address such stability issues include controls for inverter-based wind turbine generators, which reduce inertia and weaken the power system. These controls make it possible to achieve higher wind power penetration in a conventional power system. IEC Type 4B is the recommended composite frame used for this implementation and is presented in Fig. 5.

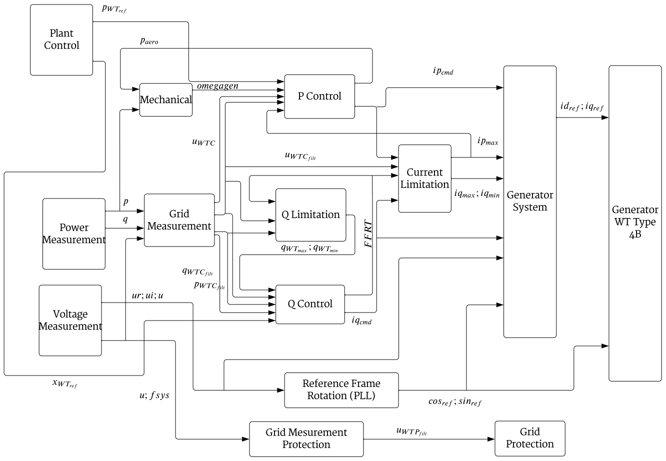


Fig. 5. Composite frame model of wind turbine type 4B [23]

III. SIMULATION RESULTS

A. Base Case Scenario

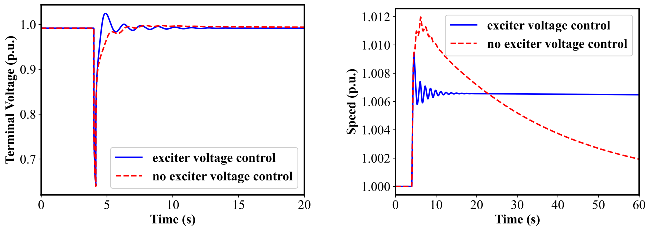
1) Initial Simulations for the Base Model: First, a power flow was performed using data from historical dispatches during peak demands of 2017 and 2018. This is done to check whether the results of these historical dispatches will mimic the power flows in the Dutch Transmission System. The information found in public sources determines the peak demand power distributed in each region.

2) Dynamic Simulation of Control Systems: After obtaining the desired results in the power flow, the system's response is assessed in the presence and absence of each control system, such as the exciter and the governor. A short-circuit event of 150 ms is applied to test different control systems. While testing is done in various iterations, only the most significant results are discussed in this paper.

A load event is also performed in a terminal with and without synchronous generation to show the system response with and without the different generator controls.

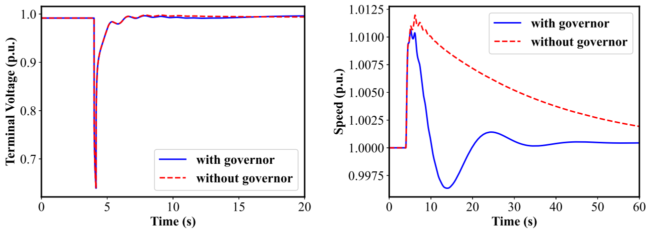
a) Exciter: In this scenario, the exciters' influence on the system's dynamic response is evaluated. Fig. 6a presents the response of the terminal voltage with the exciter. The voltage recovery is faster than in the scenario without the exciter; however, the overshoot value is more significant due to the controller action. In Fig. 6b, we observe that with the controller, there is also an overshoot in the speed response. An increase in the current flow causes the terminal voltage to drop. The exciter senses the voltage decrease and increases the strength of the magnetic field to return the voltage to the desired level. Due to the absence of a speed governor, the speed decreases as shown in the Fig. 6b.

b) Governor: The governor provides primary speed control and, therefore, active power and frequency control. For this reason, its influence on the dynamic response needs to be assessed. From Fig. 7a, it is possible to conclude that the governor does not have an important influence on voltage control, except for a reduction in oscillations, since it is controlled mainly by the exciter in each generator of the system. Fig. 7b presents the synchronous speed response, showing how the governor has a significant influence on the faster recovery of this variable in comparison to the case without this control loop. This is because the governor controls the turbine speed and ensures the generator maintains the system frequency, despite changes in terminal voltages.



(a) (b)

Fig. 6. Response of synchronous generators variables under exciter sensitivity (a) Terminal voltage magnitude (b) Synchronous speed



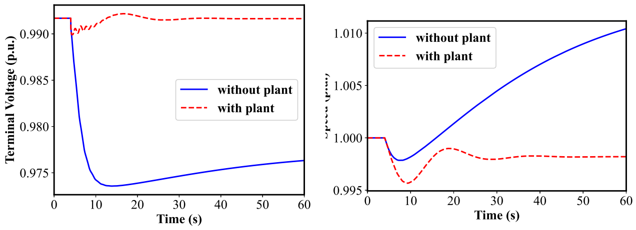
(a) (b)

Fig. 7. Response of synchronous generators variables under governor sensitivity (a) Terminal voltage magnitude (b) Synchronous speed

In the absence of a governor, the generator lacks immediate response mechanisms to changes in system frequency caused by short-circuits. However, the inherent system inertia allows them to maintain relatively stable active and reactive power outputs momentarily. Therefore, a significant change is observed only in the speed plot.

c) Load Event: In this scenario, a load event is introduced, increasing the active power of a general load by 15%. The system's response to this event is shown in Fig. 8. Fig. 8a presents the voltage at the corresponding terminal. When the controllers of the synchronous generators are not operating, there is a sudden collapse in terminal voltage due to the high power demand. The exciter maintains the terminal voltage when the controllers operate, ensuring stability during load variations. Fig. 8b presents the speed of a synchronous machine without any control. The speed increases, leading to instability. When the controllers operate, the governor adjusts the turbine's output to match load changes and maintain the system's frequency.

The sudden loss of generation or load caused by an outage event leads to deviations in voltage and frequency. The exciter and governor respond to stabilize these variables.



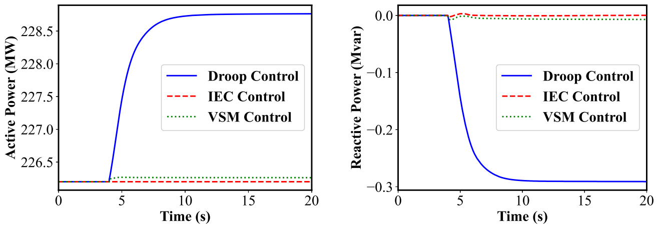
(a) (b)

Fig. 8. Response of synchronous generators variables under load event (a) Terminal voltage magnitude (b) Synchronous speed

B. High Renewable Integration Scenarios

Three cases are established to study the impact of high renewable integration in the 2030 model. Each case is categorized based on which generation is dominant: the first one with only wind generation, the second one with only solar generation, and the third one with a mix of both types of generation. The cases are designed to evaluate various VRES penetration levels. A case includes variations of generation, demand, and imports or exports. Base cases include the participation of conventional generation, wind, and solar in different combinations.

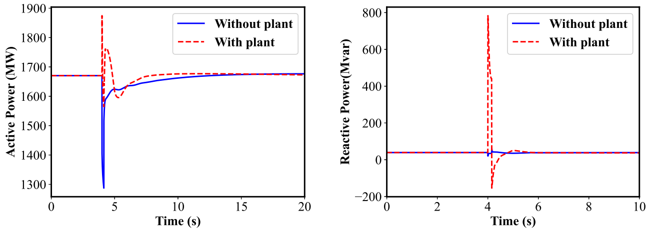
1) Case A: Only Wind Generation: In this case, wind power generation supplies the entire power demand of the system, and the three control systems mentioned in section II-D are tested. A load event is simulated with an active power load step increase of 15%. While the systems behave as predicted, there are critical disturbances that the IEC type 4B control system cannot handle. The system response is presented in Fig. 9. Fig. 9a shows the active power of the system. The droop control system imitates the droop characteristic of generators in a traditional power system by controlling the output voltage and frequency of the voltage source inverter (VSI) depending on the variation of the output power. Fig. 9b presents a similar response of the droop controller to control the reactive power and therefore the voltage at terminals.



(a) (b)

Fig. 9. Response to different control systems in a system with only wind generation (a) Active power response, (b) Reactive power response

2) Case B: Only Solar Generation: In this case, the system incorporated exclusively solar generation. The objective is to evaluate the system's dynamic response when its total power generation comes from photovoltaic plants, with and without the operation of synchronous generation, which provides reactive power and assists in the system's recovery after events. In this scenario, a short-circuit event with a duration of 150 ms is applied at one of the terminals. The response of the system is presented in Fig. 10. The active power is presented in Fig. 10a. As we expected, with synchronous generators, the power achieves the reference value faster compared to the case without the generators. The reactive power is shown in Fig. 10b. As solar power plants typically lack inertia, the active power reduces rapidly due to the sudden voltage drop during a short-circuit. Also, we can confirm how synchronous generators contribute inertia and fault-current support, helping stabilize the power system during a short circuit event.

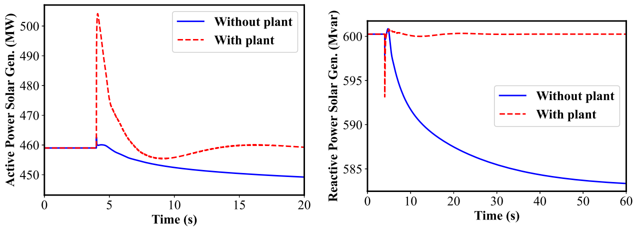


(a) (b)

Fig. 10. Response to short-circuit event of solar exclusive generation system with and without synchronous generation support (a) Active power response, (b) Reactive power response

Regardless, the solar power plants are assigned Constant-V local controllers, which prioritize voltage stability and regulate the generator's voltage output to remain constant. This means that "local control" allows voltage regulation autonomously by the generator itself without the involvement of external commands from the power system operator or central control system. The almost straight response of reactive power is due to this reason. In the presence of a plant, the generator's excitation system (REEC_B) enhances voltage stability, leading to a rapid increase in reactive power output.

3) Case C: Mix of Solar and Wind: Case C is simulated with a mix of solar and wind energy, which are dispatched with 4.5 GW (21.2%) and 16.7 GW (78.77%), respectively. An outage event of a synchronous generator is simulated. The synchronous generator does not contribute to the generation capacity, so its outage does not directly impact the available power supply. Therefore, the objective is to evaluate the system's reliability with only renewable generation operating. Fig. 11 presents the system's response under this event. Fig. 11a and Fig. 11b present the active power and reactive power response of the solar generators, respectively, showing the importance of the synchronous generators in the dynamic response. In a high VRES penetration system, sudden changes in renewable energy output can cause frequency fluctuations. Without the stabilizing influence of the synchronous generator, the frequency may exhibit variations without other synchronous generators to support the stability performance during faults. As the generator is not actively generating power, it provides reactive power support to maintain voltage levels within acceptable limits.



(a) (b)

Fig. 11. Response to outage event of mix of solar and wind exclusive generation system with and without synchronous generation support (a) Active power response, (b) Reactive power response

IV. CONCLUSIONS

A synthetic digital model of the Dutch EHV power system was successfully implemented for stability research in present and future scenarios.

Technical parameters for key components such as generator ratings, control types, and load characteristics follow standardized values from literature and public sources, ensuring consistent simulation behavior across scenarios.

The 2017-2019 scenario presents a stable system behavior attributed to the dominance of conventional generation. While the model is synthetic and based on public data, the behavior observed aligns with documented operational conditions in Dutch grid reports, lending confidence to its structure. Regardless, further work is needed for model verification.

In the 2030 scenario, the primary focus of transient studies was to implement control systems for solar and wind generation. While the analysis focused on describing system responses, key patterns, such as reactive power support improvement and frequency stability, highlight critical areas for future control strategy development and system reinforcement.

The 2030 scenario represents a relatively near-term outlook, yet the implemented dynamic stability and load models serve as a foundation for exploring longer-term scenarios, such as 2050 and beyond.

V. FUTURE RESEARCH

Battery Energy Storage Systems (BESS) will be included in the model in future studies according to [24], since BESS can significantly improve stability, Reactive power compensation devices (e.g., FACTS, electrolyzers) and grid-forming converters (GFM) should also be considered to study a wider set of future power system scenarios.

Region-specific load profiles for different times of the day could be incorporated after storage integration to study the impact of variable demand on dynamic stability.

Although the primary objective of this work was to develop the base synthetic model, future studies will focus on detailed sensitivity analyses of key parameters that may contribute to instability in future power systems.

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